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Published in:
Nihon Kokai Gakkai Ronbunshu

Publication date:
2016

Document Version
Peer reviewed version

Improved Wave-vessel Transfer Functions by Uncertainty Modelling

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Summary

This paper deals with uncertainty modelling of wave-vessel transfer functions used to calculate or predict wave-induced responses of a ship in a seaway. Although transfer functions, in theory, can be calculated to exactly reflect the behaviour of the ship when exposed to waves, uncertainty in input variables, notably speed, draft and relative wave heading, often compromises results. In this study, uncertainty modelling is applied to improve theoretically calculated transfer functions, so they better fit the corresponding experimental, full-scale ones. Based on a vast amount of full-scale measurements data, it is shown that uncertainty modelling can be successfully used to improve accuracy (and reliability) of theoretical transfer functions.

Keywords : Navigational instrument and measurement, transfer functions; uncertainty modelling; frequency-dependent model uncertainty factor; improved prediction of short-term ship responses.

1. Introduction

Reliable and accurate short-term predictions of wave-induced vessel responses are the ultimate goal in decision support systems for safe and efficient ship operations at sea. In this context, *short-term* refers to time scales in the order 30 minutes to a couple of hours. Typically, the predictions rely on a mathematical model where fundamental inputs are information about the sea state, i.e. the waves, and information about how waves, in theory, are *transferred* into ship responses; with the relationship often given in terms of theoretically calculated wave-vessel transfer functions. Obviously, the better the mathematical model, the more reliable (and accurate) the prediction of the responses[(1),(2),(3)].

Information about the on-site sea state can be obtained through different estimating means, e.g., a wave radar or the wave buoy analogy[(4),(5)]. The estimate can, in any case, be accurate or less accurate and, independently, the estimate is associated with a non-quantifiable uncertainty measure, since the *true* comparative base of the sea state, in practice, never can be obtained. On the other hand, the uncertainty of the theoretically calculated wave-vessel transfer functions can be evaluated and quantified by making a comparison to measurements of corresponding responses.

2. Uncertainty Modelling Used to Improve Transfer Functions

This study is mainly concerned with *uncertainty modelling* used to improve the accuracy of a vessel's wave-induced transfer functions and, thus, further used to improve accuracy of short-term response predictions.

Basically, the study is a compressed and updated version of a recent Master's of Science work, cf. Bach[(1)], that has a content similar to a previous work by Guedes Soares[(3)]. However, while the latter work considers model-scale experiments only, Bach[(1)] deals with full-scale operational data obtained from a large, in-service, container ship. Moreover, as shown in Section 3, the present study considers a quadratic regression model which is an extension to the linear regression model by Guedes Soares[(3)].

In the present study, the transfer function of the absolute vertical motion at a given longitudinal position, off the ship's centreline, is determined experimentally. This calculation is possible since the wave spectrum is continuously measured by wave radar. The obtained transfer function is compared to a theoretically calculated transfer function provided by third party. If variation is found between the experimental transfer function and the theoretical one, an uncertainty model is established to adjust and correct the theoretical transfer function by multiplication with a *model uncertainty factor*.

Transfer functions of other responses are studied by Bach[1], but because of space limitations the present paper focuses on only one of the responses; i.e. the vertical motion. This particular response, however, couples several motion components (heave, roll, pitch) because the motion component applies to a given longitudinal position off the centreline (and not to the ship's centre of gravity).

3. Model Uncertainty Factor

Having available the measured (full-scale) transfer function $\widehat{\Phi}(\omega)$ and a corresponding theoretically calculated function $\Phi(\omega)$ for a range of wave frequencies ω, the basic idea is to minimise the squared difference

$$\left|\widehat{\Phi}(\omega) - h(\omega)\Phi(\omega)\right|^2 \tag{1}$$

by optimisation of the factor $h(\omega)$ considering the entire interval of frequencies by summation. Indeed, $h(\omega)$ represents the model uncertainty factor and in this study three formulations are used: 1) a frequency-independent (FI) factor, 2) a linear frequency-dependent (LFD) one, and 3) a quadratic frequency-dependent (QFD) factor; given by, respectively

FI: $$h(\omega) = a \tag{2}$$

LFD: $$h(\omega) = b\omega + c \tag{3}$$

QFD: $$h(\omega) = d\omega^2 + e\omega + f \tag{4}$$

Basically, the fitting parameters $\{a\}$, $\{b,c\}$ and $\{d,e,f\}$ reflect the uncertainty related to input variables given to the theoretical transfer function. In this study resembling previous work[1],[2], the dominating variables are considered to be speed U, heading β and draft D, so that the model uncertainty factor, implicitly, depends on these variables $h(\omega) \equiv h(\omega|U,\beta,D)$.

The solution of Eq. (1) constitutes the optimum values of the fitting parameters for a specific set of measurements data with given operational variables (U, β, D). On the other hand, if all sets of available measurements data are considered simultaneously, it is possible to establish a regression model to account explicitly for uncertainties in the operational variables.

The initial work by Bach[1] formulates both a linear regression model and a quadratic one, but herein the latter only is considered. The applied model reads

$$\hat{h} = \alpha_0 + \alpha_1 U + \alpha_2 \beta + \alpha_3 D + \alpha_4 U\beta + \alpha_5 UD + \alpha_6 \beta D + \alpha_7 U^2 + \alpha_8 \beta^2 + \alpha_9 D^2 \tag{5}$$

Obviously, the particular formulation could be debated and further studies might, for instance, investigate whether some (coupling) terms could be neglected.

4. Results of the study

The content, or the results, of the study can be summarised to be composed of three subsets, basically obtained in three subtasks: 1) Determination of the experimental transfer function via measurements; 2) Comparison of the theoretical transfer function to the obtained experimental one; and 3) Adjustment of the theoretical transfer function to better fit the experimental transfer function via uncertainty modelling (Eqs. 2-5).

Fig. 1: Upper plot; CMA-CGM Rigoletto. Lower plot; geographic positions of measurements: 1) August 12th, 2) August 20th, 3) September 16th, 4) September 20th, and 5) October 2nd. Around each position, 24 hours of continuous data have been recorded.

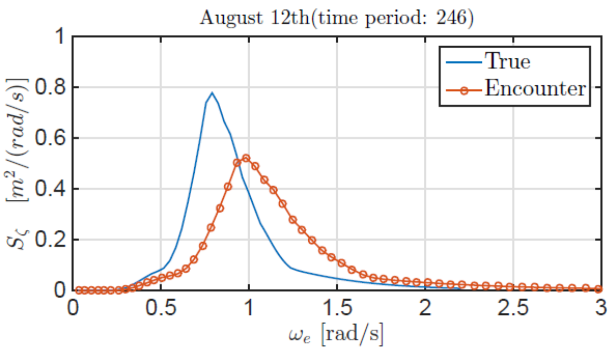

Fig. 2: Sample wave spectrum of time period no. 246 shown in both true wave frequency domain and in encounter frequency domain.

Sample results of the study can be seen in Figures 3 and 4, and the studied vessel and geographic positions of the vessel during the measurement periods are shown in Figure 1. During all measurement periods, the wave spectrum has been estimated using X-band marine radar. One case of an estimated wave spectrum for a specific time span, time period no. 246, arbitrarily selected from the full data set comprising the five days of measurements, is shown in Figure 2. Kindly note that the spectral ordinates, $S_\zeta(...)$, of the wave spectrum is shown for encounter frequency, ω_e, with legend 'Encounter' as well as for the corresponding true wave frequency, ω_0, with legend 'True'; although only ω_e appears as label on the abscissa. The relationship between true wave frequency and encounter frequency is controlled by the Doppler shift.

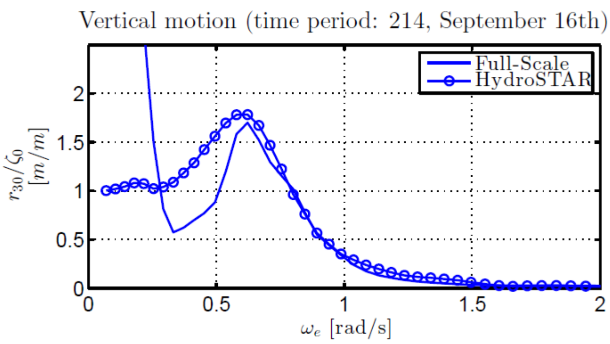

Fig. 3: Comparison of experimental ('Full-Scale') and theoretical ('HydroSTAR') transfer function.

The transfer function of vertical motion, r_{30}, is shown in Figure 3 in non-dimensional form by division with wave amplitude ζ_0. In the one case, legend 'Full-Scale', the result has been derived from full-scale measurements, whereas the other case, legend 'HydroSTAR', is based on calculations obtained by Bureau Veritas' hydrodynamic software. Via modelling of a vast amount of data, basically given in terms of comparisons between the theoretical transfer function and the corresponding experimental one, see Figure 3, three uncertainty models, Eqs. (2)-(4), are established to account for uncertainties with respect to input values to the theoretical transfer function. As pointed out previously, the models are based on a frequency-independent model uncertainty factor, a linear frequency-dependent one, and, finally, a quadratic frequency-dependent model uncertainty factor. Each of the models has been applied to the same sets of data; resulting in model uncertainty factors derived for almost a hundred time periods of measurements data. Subsequently, the quadratic regression model, Eq. (5), is fitted to describe each of the uncertainty modelling factor's behaviour on all of the available data sets together, so that the effect of uncertainties in speed, draft and relative wave heading is taken into account. Afterwards, the regression model is in the three cases, (FI), (LFD) and (QFD), used to improve the theoretically calculated transfer function. It is noteworthy that all the considered time periods (sampled at 10 Hz) have a length of 20 minutes and that they are selected when conditions are stationary. This choice is made to limit the influence of uncertainty in the calculations; except of those uncertainties associated to the values of speed, draft and relative wave direction.

The consequence of applying the quadratic regression model to two selected periods of time, chosen on August 12th (time period no. 246) and October 02nd (time period no. 101), can be seen in Figure 4. It is noteworthy that the quadratic regression model in any case, FI, LFD, QFD, respectively, has been established from the complete data set consisting of nearly a hundred time periods. Furthermore, it is necessary to apply a set of cut-off frequencies, so that the uncertainty modelling is made on a reduced frequency interval as compared to the larger interval observed from the initial comparison, see Figure 3, of the experimental and theoretical transfer functions.

The plots in Figure 4 show a general improvement of the theoretical transfer function in both of the considered cases, i.e. time periods no. 246 and no. 101. Particularly,

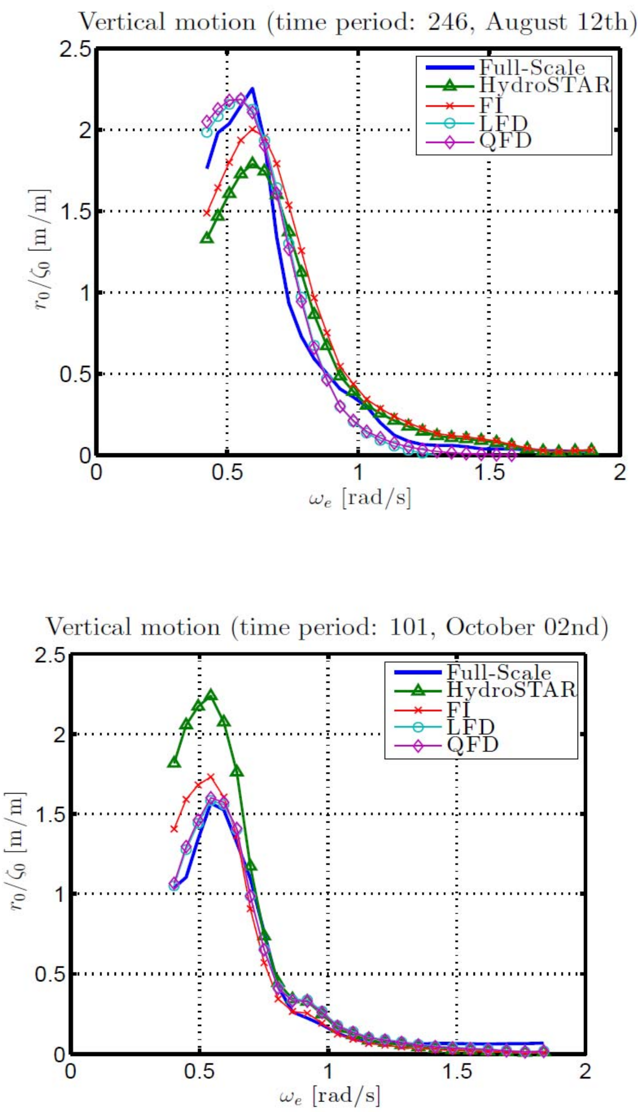

Fig. 4: Comparison of model uncertainty factors' effect on theoretical transfer functions of vertical motion. Results are shown for two arbitrarily selected time periods, i.e. no. 246 and no. 101.

a significant improvement is noted at the lower frequencies, when the linear and quadratic frequency-dependent (LFD and QFD) model uncertainty factors are applied. Overall, considering all data sets although this is not shown in the present paper, QFD is however superior to LFD.

5. Summary and Concluding Remarks

The transfer function of vertical motion has been determined experimentally for a large container ship, and the experimental results serve as a comparative base to the theoretically calculated corresponding transfer function. Based on comparison between the two sets of results, uncertainty modelling is used to improve the theoretically calculated transfer function. Particular points to note are the following:

- Three different model uncertainty factors were studied. Thus, a frequency-independent (FI), a linear frequency-dependent (LFD) and a quadratic frequency-dependent (QFD) model factor have been derived by application to a vast amount of data sets representing different operational conditions in speed, wave heading and draft.
- The effect of draft, speed and wave heading on the model uncertainty factors was studied by use of quadratic regression analysis, and a regression model was established in each case (FI, LFD, QFD).
- The three model uncertainty factors were used to improve the theoretically calculated transfer function, see Figure 4.
- Although not shown (directly) in the paper, all of the three model factors were found to decrease the total sum of error between the experimental and the theoretical transfer function.

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